RESEARCH MEMORANDUM

THE VARIATION OF ATMOSPHERIC TURBULENCE WITH ALTITUDE AND ITS EFFECT ON AIRPLANE GUST LOADS

By Robert L. McDougal, Thomas L. Coleman,
and Philip L. Smith

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

Information on the amount and relative intensity of atmospheric turbulence for altitudes up to 60,000 feet has been obtained from investigations with airplanes and balloon-borne instruments. Analysis of the data obtained indicates substantial reductions in the turbulence at higher altitudes for the weather conditions represented by the tests.

The information from these investigations may be combined with other turbulence measurements at low altitudes to estimate the gusts and gust loads for particular types of operations. Application is made to the calculation of gust loads expected for certain assumed high- and low-altitude airline transport operations. The results indicate large reductions in the number and intensity of the gusts for the high-altitude operation, but as a result of the high airspeeds anticipated for high-altitude jet airplanes during the climb and descent through the low rough altitudes, the possibility of more severe gust loads is indicated for the jet transport.

INTRODUCTION

Until recently, very little information on the frequency and intensity of atmospheric turbulence at high altitudes has been available for use in gust-load studies for high-altitude airplanes and missiles. For the last few years, information on the variation with altitude of the amount and intensity of turbulent air has been collected by the National Advisory Committee for Aeronautics with the assistance of other organizations. The purpose of this paper is to summarize the information collected with a view toward indicating the expected gust histories for high-altitude flight operations. In addition, the expected gusts and gust loads are calculated for a specified high-altitude operation to illustrate the manner in which the gust data might be applied to load calculations. The results obtained for this example are compared with those for a current airplane operation at lower altitudes as an indication of the expected trends in the gusts and loads.

SCOPE OF DATA

Turbulence measurements for altitudes up to 47,000 feet were obtained from bomber-type airplanes operated by the Air Force and the manufacturer. The measurements consisted of time-history records of airspeed, altitude, and acceleration taken with VGH recorders (ref. 1). The acceleration data were obtained from electrically combined accelerometers installed at the estimated nodal points of the fundamental bending mode of the wing. The scope of these data in terms of miles flown within different altitude intervals is given in table I. The flights were conducted mostly over continental United States and about an equal flight time is represented for each season of the year. The turbulence encountered was due mostly to light convective activity and wind shear. Turbulence associated with thunderstorms or severe convective activity does not appear to be present in the data evaluated.

Additional turbulence measurements for altitudes up to 60,000 feet were obtained from soundings of the NACA turbulence telemeter. This instrument is carried aloft by a balloon and transmits a record of the vertical accelerations experienced by a stable parachute on the descent following balloon burst. The scope of these data in terms of number of soundings within different altitude intervals is also given in table I. The data were collected with the cooperation of the United States Weather Bureau from daily soundings taken over a period of about 1 year at stations located at Caribou, Maine; Grand Junction, Colorado; Greensboro, North Carolina; and Miami, Florida. For the highest altitude intervals, the turbulence was most likely associated with clear-air conditions. In these data, also, turbulence associated with thunderstorms and severe convective activity does not appear to be present.

EVALUATION OF DATA

Airplane.- The records obtained from the airplane flights were evaluated to obtain a measure of the vertical and horizontal components of the gusts, and the horizontal extent of the turbulent areas encountered.

The vertical gust velocities were derived from the gust load formula and the gust factor of reference 2. The reading threshold for the acceleration records was 0.08g, and for the average flight weight, the corresponding gust velocity threshold was about 2 fps. The gust velocities evaluated by the method of reference 2 are the estimated average velocities over the span of the airplane, and although they are not the actual velocities because of simplifying assumptions made in deriving the gust formula, they are used herein as a consistent measure of the gust intensities at different altitudes.

The horizontal gust velocities were evaluated from the airspeed records by reading the one-half amplitude fluctuations in the indicated airspeed. All fluctuations above a threshold of 2 fps were evaluated.

In evaluating the VGH records for the horizontal extent of the turbulent areas, rough air was defined by any portion of the accelerometer or airspeed record in which the trace was continuously disturbed and contained acceleration increments or airspeed fluctuations equal to or greater than 0.08g and 2 fps, respectively. The summation of the lengths of the individual areas of rough air was divided by the total flight distance for given altitude intervals to obtain the percent of rough air for that altitude interval.

Telemeter.- The telemeter records were evaluated to obtain the thickness of each layer of turbulent air noted on the records, the relative amount of turbulent air within the different altitude intervals, and the gust velocities. These evaluations of the telemeter data were based on wind-tunnel tests and analytical studies of the response of the parachute to vertical gusts. Problems connected with the evaluation of the telemeter data such as the effects of changing parachute stability with altitude have not been completely resolved and may have some influence on the results. Analysis to date indicates that such effects may lead to overestimations of the turbulence intensities at the highest altitudes.

For the present analysis, any portion of the telemeter record which indicated that the parachute was continuously disturbed and contained gusts equal to or greater than the reading threshold of 1 fps was classified as rough air. The percent of turbulent air within each 10,000-foot altitude interval was obtained from the summation of these rough layers divided by the total vertical descent distance through the interval.

RESULTS AND DISCUSSION

In the subsequent analysis of the data obtained from the airplane and the telemeter, no attempt has been made to combine the gust velocity data from the different methods of measurements since the velocity as evaluated in some cases is at best only an approximation to the actual velocity of the gust. Each set of data, however, presumably gives a reliable measure of the relative variation of the gust or turbulence intensities with altitude. This variation in the intensity and the amount of the turbulence with altitude is discussed in the subsequent sections.

Intensity of turbulence.- Cumulative frequency distributions for different altitude intervals were obtained from the gust velocities evaluated from the accelerometer and airspeed records taken on the airplane and from the acceleration records taken by the telemeter. These distributions for each sample of data were then divided by the distance in turbulent air as previously defined for the given altitude intervals to obtain the average number of gusts of given intensities that were encountered per mile of rough air.

In order to show the variation in the gust intensity with altitude, the maximum gust velocity expected for a given flight distance in turbulent air at various altitudes was divided by the maximum gust velocity expected for the same flight distance in turbulent air at the lowest altitude. These ratios for the three samples of data are shown plotted against altitude in figure 1. The curve has been faired through the data points in the figure to show the mean variation in the relative gust intensities with altitude.

Consideration of figure 1 indicates a definite decrease in the gust velocities with altitude, the decrease being about 10 percent for each 10,000-foot increase in altitude. The differences noted between the three samples of data in the figure do not appear large, and in view of the size of each sample, the trend shown in figure 1 would appear to be well-established.

Amount of turbulence.- Comparisons of the amount of turbulent air at different altitudes as evaluated from the airplane and telemeter records indicated good agreement between both the airplane and the telemeter data. Accordingly, a curve faired through both samples of data is used to show the percent of turbulent air for the altitude range of the tests. The results are shown in figure 2. As will be noted from this figure, a rapid reduction in the amount of turbulent air occurs as the altitude is increased through the lower layers which are characterized by convective activity, and a smaller reduction occurs at higher altitudes where wind-shear effects predominate. Above an altitude of about 25,000 feet, figure 2 indicates that turbulence could be expected, on the average, less than 5 percent of the time.

Size of turbulent areas.- Both the horizontal extent and the vertical thickness are used to define the size of the turbulent areas. Since the major interest is at the higher altitudes, these data on the size of the turbulent areas are shown only for altitudes above 20,000 feet.

The distribution of the horizontal extents, or lengths, of the turbulent areas as determined from the airplane records is given in figure 3 for class intervals of 10 miles. The distribution is based on 1,000 areas. The figure indicates that the number of turbulent areas decreases rapidly as the length increases and that areas having a length greater than 50 miles can be considered unusual. The VGH records indicated that the turbulent areas were generally encountered in groups in given regions of the flight path and that many of the areas in a group were separated by only short lengths of smooth air (2 to 3 miles). Since these short intervals of smooth air would not necessarily be distinguished by a pilot in making reports of rough air, the majority of the turbulent areas in figure 3 are of smaller extent than the areas contained in the summary of pilots' reports in reference 3.

The distribution of the vertical thicknesses of the turbulent areas as determined from the telemeter records is given in figure 4 for class intervals of 200 feet. The distribution shown in figure 4 is similar to figure 3 and indicates that the majority of the turbulent areas have a thickness of less than 800 feet. It was also noted from the telemeter records that many of the areas were encountered in groups with an altitude separation between areas in some cases of only 100 or 200 feet of smooth air.

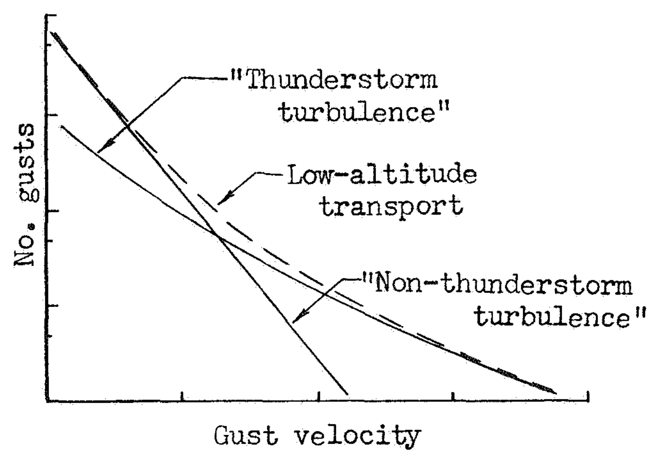
Other observations.- In addition to the information shown in figures 1 to 4, the VGH and telemeter data were also examined to determine possible effects of such factors as season or geography on the turbulence. Studies of the telemeter data showed no significant variation from the results shown in figures 1 and 2 with the geographic location of the station. A slight seasonal variation was noted, however, and it appeared that the percentage of turbulent air for given altitudes was somewhat greater during the winter months than for other seasons. The distributions of the lengths and thicknesses of the turbulent areas (figures 3 and 4) showed no variation with altitude for levels above 20,000 feet. Below 20,000 feet the more extensive areas became more frequent.

APPLICATION TO AIRPLANE OPERATIONS

General Considerations

The application of gust statistics to the calculation of the gusts and loads for assumed operations requires the integration of the gusts and loads for the expected weather conditions along the entire flight path. Although the high-altitude data presented in the previous sections are believed to represent adequate quantitative samples, as pointed out earlier there is reason to believe that severe convective or thunderstorm activity is not adequately represented because of the nature of the airplane operations and the characteristics of the telemeter. It thus does not appear feasible to use the gust statistics obtained without making adjustments for the significant gusts and loads normally associated with storms.

In order to assess the contribution of severe convective activity or thunderstorms to the gusts encountered by transport airplanes, the gust data in reference 4 from operations of a low-altitude transport were examined. This examination indicated that the gust distribution could be synthesized by a combination of two distributions - one distribution representing the more severe turbulence generally associated with thunderstorms and towering cumulus clouds and the second representing the lighter turbulence associated with other weather conditions. The category light turbulence was taken to cover a variety of weather conditions and included turbulence associated with airflow over rough terrain, wind shear and light convective activity. For convenience of presentation, these two distributions will be referred to herein as "thunderstorm" and "non-thunderstorm" turbulence distributions. The gust distributions for the non-thunderstorm and thunderstorm turbulence were obtained from references 5 to 7 and are shown in figure 5. The various distributions scattered somewhat as shown by the cross-hatched areas in figure 5, but for the present purposes the two distributions shown were chosen. By use of the two distributions in the figure, it was found that the low-altitude transport data of reference 4 were approximated by combining roughly 18 percent of the flight time under the less severe non-thunderstorm turbulence conditions and 0.1 percent of the flight time in thunderstorm conditions.



In order to illustrate the procedure used, the accompanying sketch shows the over-all distribution of gust velocity for the low-altitude transports and the two separate distributions which represent 18 percent of the non-thunderstorm turbulence distribution and 0.1 percent of the thunderstorm distribution of figure 5. It will be noted from the sketch that the shape of the distribution for the low-altitude transport operations is approximated quite well at the low gust velocities by the data for non-thunderstorm turbulence and at the higher gust velocities by the data for thunderstorm turbulence.

Gust Distributions

Non-thunderstorm turbulence.- In view of the success achieved in approximating the gusts for the low-altitude transport operations by the use of simple distributions representing non-thunderstorm turbulence and thunderstorm conditions, it appeared reasonable to utilize a similar procedure for the higher altitudes making use of the gust statistics presented earlier. The non-thunderstorm turbulence for each altitude was estimated from the distribution for this type of turbulence at low altitudes as shown in figure 5 and the results of figures 1 and 2 which describe the decrease with altitude of the intensity and amount of the turbulence. A family of distributions for the non-thunderstorm turbulence at the various altitude intervals was obtained by multiplying the distribution of figure 5 by the ratio of gust velocities given in figure 1 for the different altitudes. The variation with altitude in the amount of the non-thunderstorm turbulence was obtained from figure 2 and the values read are tabulated in table II for several altitude brackets. Multiplication of the pertinent distribution by the percent of rough air given in table II for each altitude interval then gave the contribution of the non-thunderstorm turbulence to the gusts that would be expected per mile of flight at each altitude.

Thunderstorm turbulence.- The contribution of the thunderstorm turbulence was estimated from figure 5 by assuming that the gust distributions for thunderstorms did not vary significantly with altitude (ref. 7). The proportion of flight time in thunderstorm conditions for various altitudes was estimated from considerations of data on thunderstorm heights as given in reference 8 and qualitative considerations of the probability of avoidance by visual means. The expected proportion of flight in thunderstorms obtained in this manner is shown in table II. The gusts contributed by the thunderstorms per mile of flight at each altitude was then obtained by multiplying the distribution for thunderstorms in figure 5 by the relevant proportion of flight distance in these conditions from table II.

Total gust distributions.- In order to obtain the total gust distribution for both the non-thunderstorm and thunderstorm-type turbulence, the results discussed in the preceding paragraphs were added to give a family of curves covering the altitude range from 0 to 60,000 feet. These distributions are given in figure 6 and represent the average number of gusts of different intensities due to the lighter and more severe turbulence that would be expected per mile of flight within the indicated altitude interval. The gusts encountered for a particular operation can be found by multiplying each distribution in figure 6 by the appropriate flight distance within the altitude interval. The application of this procedure for an assumed set of airplane operations is made in the following section.

Illustrative Example

In order to illustrate how the foregoing gust distributions might be applied to actual operations and to indicate the possible trends in gust loads with altitude, the gusts and gust loads for a low- and a high-altitude airline operation are computed from the gust distributions in figure 6. The altitude and airspeed profiles of the two operations assumed are shown in figure 7. For purposes of comparing the gusts and loads, a series of flights of the type shown in figure 7 and totaling 10^7 miles is used for each operation.

The low-altitude operations used in this example are considered representative of present-day transport flights with a cruising altitude of about 20,000 feet. The high-altitude operations are assumed to represent future jet transport flights with the cruising altitude increasing from about 35,000 to 45,000 feet as the flight progresses. In addition to this difference in the altitudes, significantly higher airspeeds during climb and descent are shown in figure 7 for the jet transport. Although data are not available from actual jet transport operations, these high airspeeds are typical of the values measured for operations of jet bomber airplanes on not only military missions but also on simulated transport operations. In view of the lack of data on jet transports, the airspeeds shown in figure 7 are used in the calculations.

Comparisons of gusts.- In order to estimate the gusts that would be encountered for the two operations in figure 7, the flight distance within each altitude interval was determined from the airspeed and altitude profiles. The gust distributions for the various altitude intervals of figure 6 were then multiplied by the pertinent flight distance to obtain the number of gusts of different intensities that would be expected at each altitude. The summation of these gusts for each operation yielded the two distributions shown in figure 8.

Comparison of the distributions in figure 8 indicates substantially fewer gusts for the future high-altitude operation than for the present-day operation. The curves indicate a reduction of about 3 or 4 to 1 in the number of small gusts (10 fps), and a reduction of almost 10 to 1 in the number of large gusts (40 fps). These reductions are a direct reflection of the fewer numbers of gusts shown in figure 6 for the high altitudes.

Comparison of accelerations.- The gust accelerations were computed from the gust velocities evaluated for the different altitude intervals of each operation and the associated airspeeds. These computations were made by use of the gust load formula and the gust factor of reference 2. With the exception of the airspeeds, other airplane characteristics such as lift-curve slope or variation in wing loading due to fuel consumption were considered the same for each operation in order to show only the effect of the different operating altitudes and airspeeds on the accelerations. The resulting distributions are shown in figure 9.

Figure 9 indicates that in spite of the decreases in the gusts noted previously, the acceleration increments are larger for the high-altitude jet transport due to its higher speeds in climbing and descending through the lower and more turbulent altitudes. The figure indicates that acceleration increments greater than about 1 g are almost 5 times as frequent for the high-altitude jet operation as for the present-day operation. Analysis has indicated that the frequencies of occurrence of the accelerations are very sensitive to a change in airspeed for the climb and descent portions of the flights; for the present example, reducing the climb and descent speeds of the jet airplane to the same speeds as for the low-altitude airplane would decrease the number of 1 g acceleration increments by a factor of 8 or 10. Other analysis has indicated that changes in airspeed or percent of flight time for cruising altitudes above 20,000 feet have relatively small effects on the total number of accelerations. The important part of the flight defining the loads experienced thus appears to be the time spent at the lower altitudes.

It is apparent from these results that the reductions in the number of gusts as shown in figure 8 for the high altitudes may not be reflected in a similar reduction in gust loads and that the reduction realized for any operation depends to a large extent on the airspeed in climb and descent through the lower altitudes.

CONCLUDING REMARKS

Data on the amount and intensity of atmospheric turbulence for altitudes up to 60,000 feet, obtained from soundings with telemetering instruments and time-histories of airplane accelerations and airspeed fluctuations, indicate substantial reductions in the number and intensity of gusts at the higher altitudes. In interpreting these gust data in terms of gust loads such as might be encountered in future operations at the higher altitudes with jet airplanes, however, it is necessary to take into account other factors, in particular the flight speeds and the altitude profile. A specific study made for high-speed, high-altitude operations for a chosen flight plan and flight speeds (based on available data from military and pseudocommercial operations of jet bombers, and from airline operations) shows that the number of large loads were somewhat greater than for a current type of lower altitude operation. The results obtained in this calculation indicated that for the high-speed high-altitude operation the airspeed in climb and descent through the lower altitudes had a marked effect on the over-all loads. Large reductions in the loads were obtained by reducing the airspeed during these portions of the flight.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 3, 1953

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TABLE I.- SCOPE OF TURBULENCE MEASUREMENTS OBTAINED

FROM AIRPLANE AND TELEMETER

Altitude, ft	Airplane (Flight miles)	Telemeter (No. of soundings)
0 to 10,000	29,000	---
10,000 to 20,000	42,000	700
20,000 to 30,000	66,500	800
30,000 to 40,000	24,500	800
40,000 to 50,000	21,500	750
50,000 to 60,000	------	650

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TABLE II.- VARIATION IN AMOUNT OF TURBULENCE WITH ALTITUDE

Altitude, ft	Percent flight distance in turbulence	
	Non-thunderstorm turbulence	Thunderstorm turbulence
0 to 10,000	18.0	0.10
10,000 to 20,000	6.4	.11
20,000 to 30,000	4.5	.062
30,000 to 40,000	3.9	.0067
40,000 to 50,000	3.4	.0017
50,000 to 60,000	2.2	0

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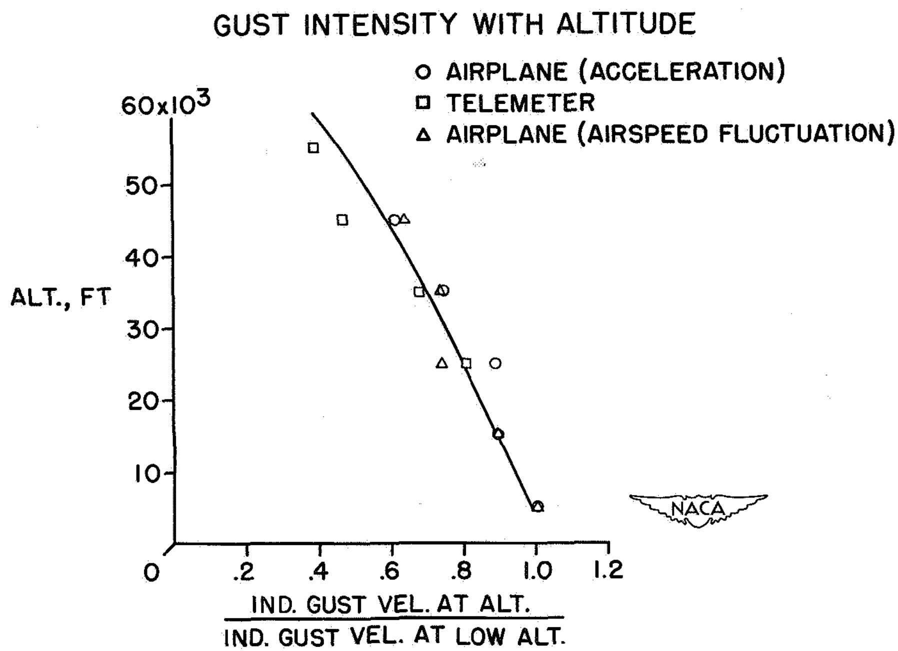

Figure 1.- Variation in relative gust velocities with altitude (non-thunderstorm turbulence).

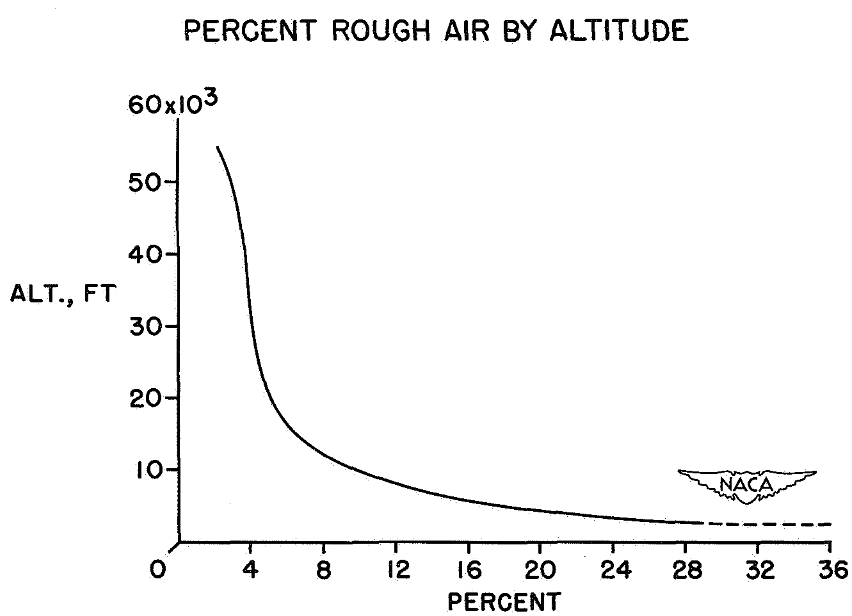

Figure 2.- Variation in percent of turbulent air with altitude (non-thunderstorm turbulence).

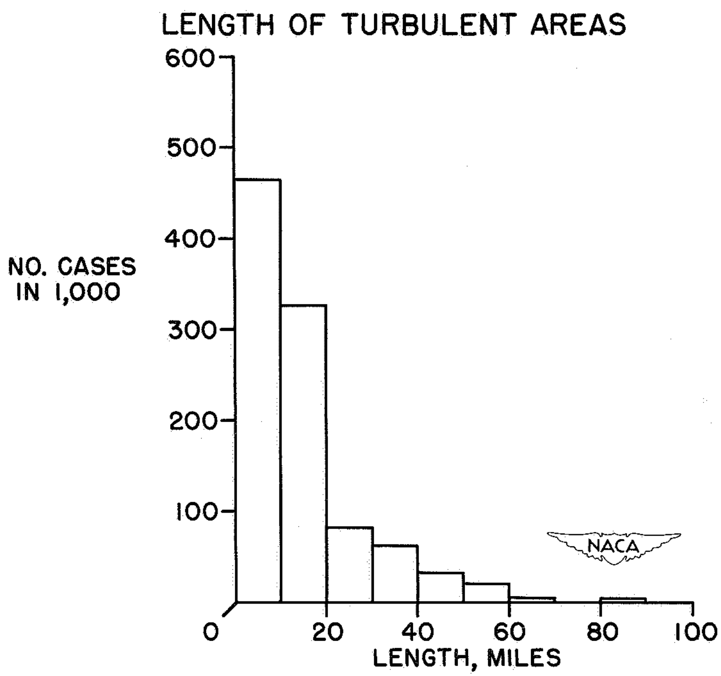

Figure 3.- Variation in length of areas of non-thunderstorm turbulence.

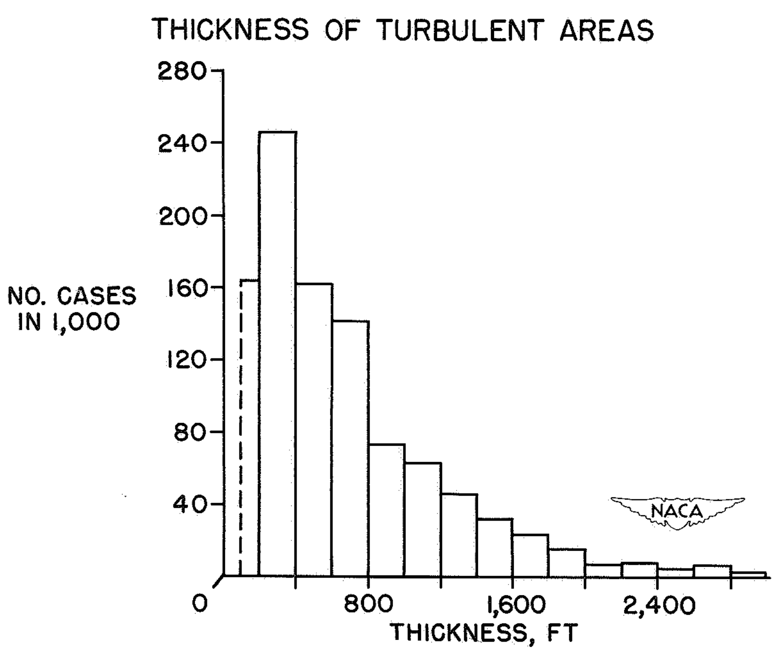

Figure 4.- Variation in thickness of areas of non-thunderstorm turbulence.

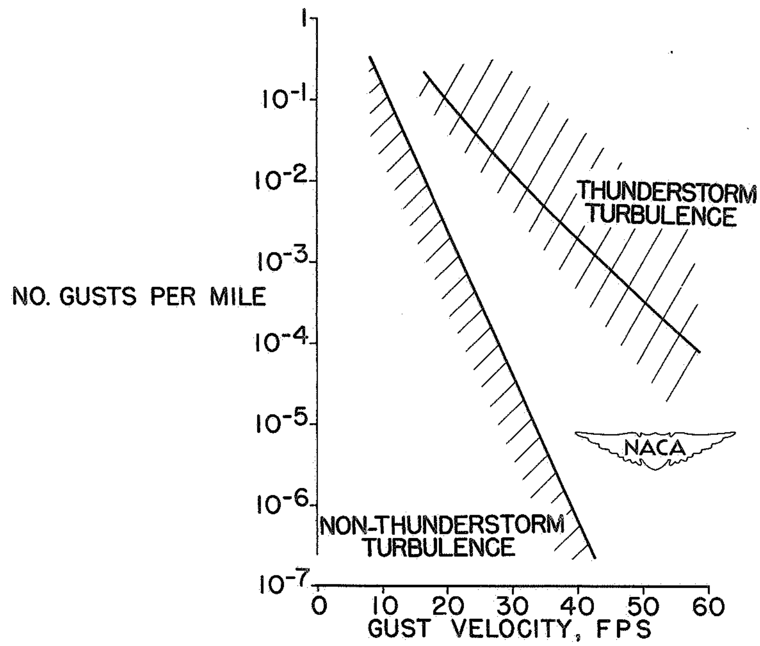

Figure 5.- Variation in number of gusts of given velocities encountered per mile of flight in non-thunderstorm and storm turbulence.

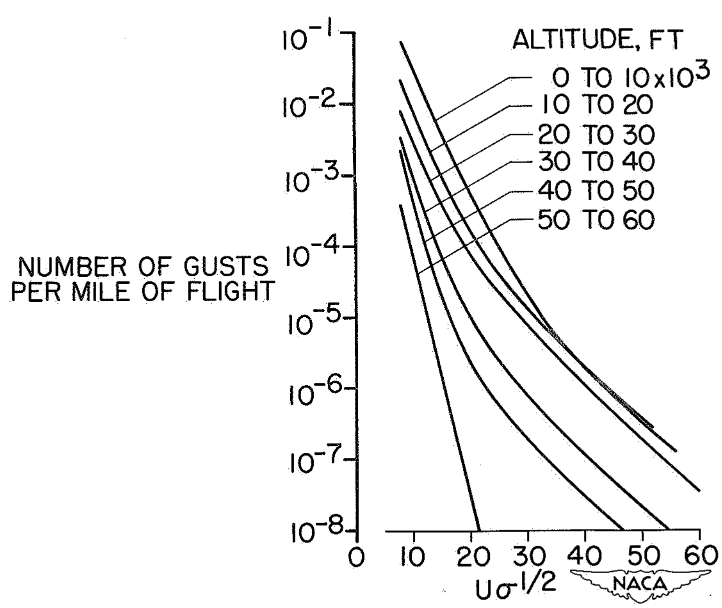

Figure 6.- Variation in number of gusts of given velocities encountered per mile of flight at various altitudes for airline operations.

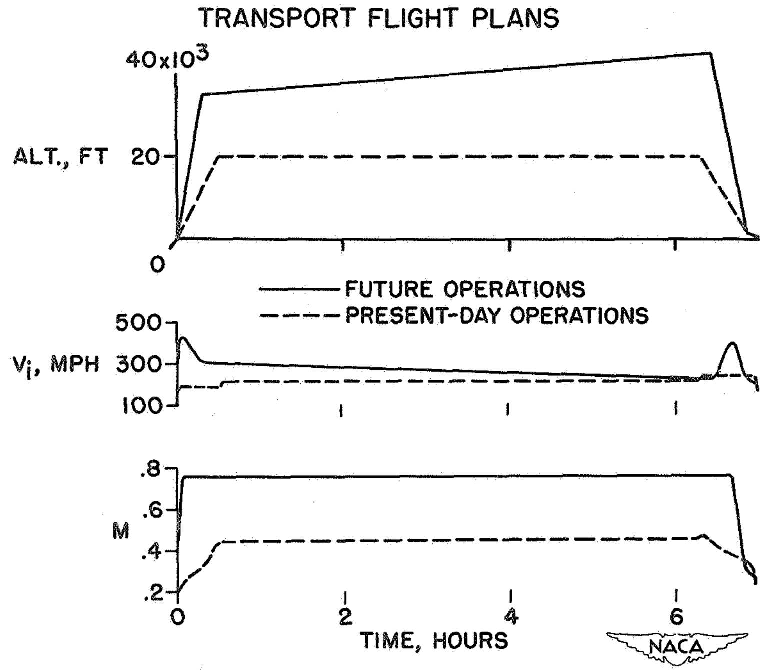

Figure 7.- Altitude, airspeed, and Mach number profiles for two assumed transport operations.

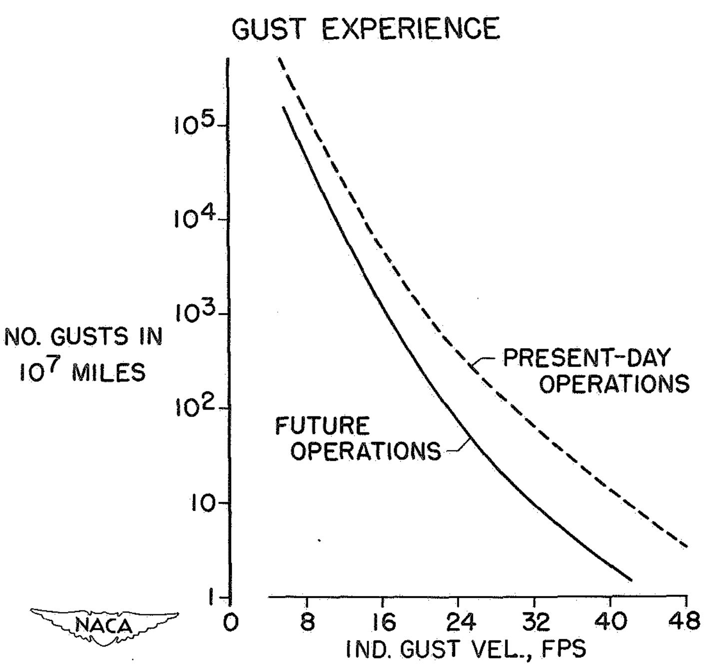

Figure 8.- Estimated number of gusts of given velocities encountered in 10^7 flight miles for two assumed transport operations.

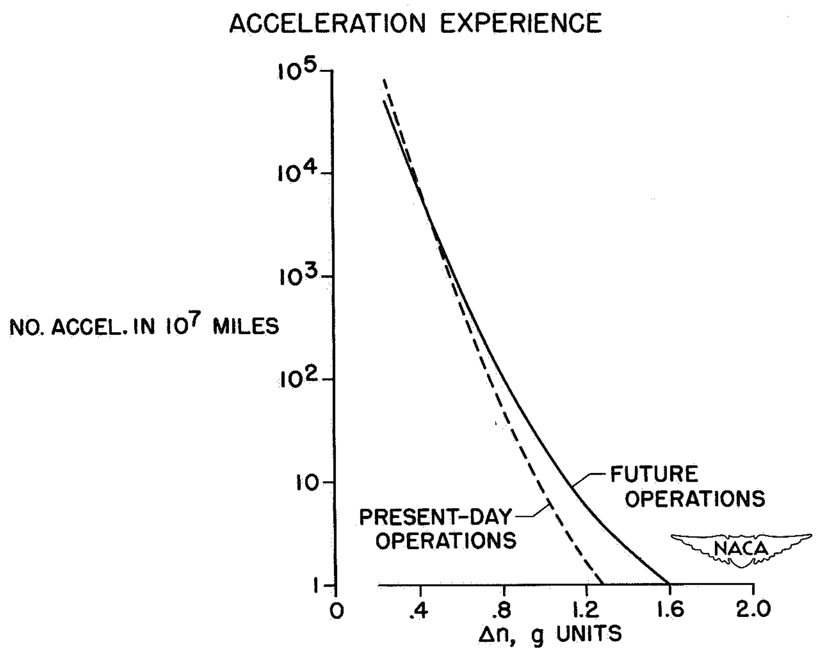

Figure 9.- Estimated number of gust accelerations of given values experienced in 10^7 flight miles for two assumed transport operations.